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1 **“1.5°C warmer worlds” not all the same**

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37 **February 19, 2018**

The UN Paris Agreement<sup>1</sup> includes a long-term climate goal with two levels of global mean temperature anomalies (1.5°C and 2°C global mean warming above pre-industrial times). However, it does not precisely define what a “1.5°C warmer world” would be like. Here we show that alternative “1.5°C warmer worlds” associated with different temporal and spatial dimensions of changes, climate variability (climate noise), model uncertainty, and mitigation and adaptation choices, overlaid on anticipated and differential vulnerabilities, can be vastly different at regional scales. Different global and regional climate sensitivities, as well as overshooting, mean that pursuing stringent 1.5°C climate mitigation will not completely remove the risk of global temperatures being much higher, and regional extremes reaching dangerous levels for ecosystems and society over the coming decades.

Since 2010, international climate policy under the United Nations moved the public discourse from a focus on atmospheric concentrations of greenhouse gases to a focus on distinct global temperature targets above the pre-industrial period<sup>1,2</sup>. In 2015, this led to the inclusion of a long-term temperature goal in the Paris Agreement that makes reference to two levels of global mean temperature increase: 1.5°C and 2°C. The former is set as an ideal aim (“pursuing efforts to limit the temperature increase to 1.5°C”) and the latter is set as an upper bound (“well below 2°C”)¹. This change in emphasis allows a better link between mitigation targets and the required level of adaptation ambition<sup>3,4</sup>.

Assessing the effects of the reduction of anthropogenic forcing through a single qualifier, namely global mean temperature change compared with the pre-industrial climate, however, also entails risks. This deceptively simple characterization may lead to an oversimplified perception of human-induced climate change and of the potential pathways to limit impacts of greenhouse gas forcing. We highlight here the multiple ways in which a 1.5°C global warming may be realized. These alternative “1.5°C warmer worlds” are related to a) the temporal and regional dimension of 1.5°C pathways, b) model-based spread in regional climate responses, c) climate noise, d) and ranges of possible options for mitigation and adaptation. We also highlight potential high-risk temperature outcomes of mitigation pathways currently considered consistent with 1.5°C due to uncertainties in relating greenhouse gas emissions to subsequent global warming, and to uncertainties in associated regional climate changes.

#### Definition of a “1.5°C warming”

Global mean temperature is a construct: It is the globally averaged temperature of the Earth that can be derived from point-scale ground observations or computed in climate models. Global mean temperature is defined over a given time frame (e.g. averaged over a month, a year, or multiple decades). As a result of climate variability, which is due to internal variations of the climate system and temporary naturally-induced forcings (e.g. from volcanic eruptions), a climate-based global mean temperature typically needs to be defined over several decades (at least 30 years under the definition of the World Meteorological Organization)<sup>5</sup>. Hence, to determine a 1.5°C global temperature warming, one needs to agree on a reference period (assumed here to be 1850-1900 inclusive, unless otherwise indicated), and on a time frame over which a 1.5°C mean global warming is observed (assumed here to be of the order of one to several decades). Comparisons of global mean temperatures from models and observations are also not straightforward: Not all points over the Earth’s surface are continuously observed, leading to methodological choices about how to deal with data gaps<sup>6</sup> and the mixture of air temperature over land and water temperatures over oceans<sup>7</sup> when comparing full-field climate models with observational products.

86

87 **Temporal and spatial dimensions**

88 There are two important temporal dimensions of 1.5°C warmer worlds: a) the time period over  
89 which the 1.5°C warmer climate is assessed; and b) the pathway followed prior to reaching this  
90 temperature level, in particular whether global mean temperature returns to the 1.5°C level after  
91 previously exceeding it for some time (also referred to as “overshooting”, Figure 1a). As highlighted  
92 hereafter, for some components of the coupled Human-Earth system, there are substantial  
93 differences in risks between 1.5°C of warming in the year 2040, 1.5°C of warming in 2100 either with  
94 or without earlier overshooting, and 1.5°C warming after several millennia at this warming level.

95 The time period over which 1.5°C warming is reached is relevant because some slow-varying  
96 elements of the climate system respond with a delay to radiative forcing, and the resulting  
97 temperature anomalies. Hence their status will change over time, even if the warming is stabilized at  
98 1.5°C over several decades, centuries, or millennia. This is the case with the melting of glaciers, ice  
99 caps and ice sheets and their contribution to future sea level rise, as well as the warming and  
100 expansion of the oceans, so that a substantial component of contemporary sea-level rise is a  
101 response to past warming. In addition, the rate of warming is also an important element of imposed  
102 stress for resulting risks, because it may affect adaptation or lack thereof<sup>8,9,10</sup>. For example, the  
103 faster the rate of change the fewer taxa (and hence ecosystems) can disperse naturally to track their  
104 climate envelope across the Earth’s surface<sup>8,11</sup>. Similarly, in human systems, faster rates of change in  
105 climate variables such as sea level rise present increasing challenges to adaptation to the point  
106 where attempts may be increasingly overwhelmed.

107 Whether mean global temperature temporarily overshoots the 1.5°C limit is another important  
108 consideration. All currently available mitigation pathways projecting less than 1.5°C global warming  
109 by 2100 include some probability of overshooting this temperature, with some time period during  
110 the 21<sup>st</sup> century in which warming higher than 1.5°C is projected with greater than 50%  
111 probability<sup>12,13,14,15</sup>. This is inherent to the difficulty of limiting warming to 1.5°C given that the Earth  
112 at present is already very close to this warming level (ca. 1°C warming for the current time frame  
113 relative to 1851-1900<sup>16</sup>). The implications of overshooting are very important for projecting future  
114 risks and for considering potentially long-lasting and irreversible impacts in the time frame of the  
115 current century and beyond, for instance associated with ice melting<sup>17</sup> and associated sea level rise,  
116 loss of ecosystem functionality and increased risks of species extinction<sup>11</sup>, or loss of livelihoods,  
117 identity, and sense of place and belonging<sup>18</sup>. Overshooting might cause the temporary exceedance  
118 of some thresholds for example in ecosystems, which might be sufficient to cause permanent loss of  
119 these systems; or, those systems and species able to adapt rapidly enough to cope with a particular  
120 rate of change would be faced with the challenge of adapting again to a lower level of warming post-  
121 overshoot. The chronology of emission pathways and their implied warming is also important for the  
122 more slowly evolving parts of the Earth system, such as those associated with sea level rise (see  
123 above).

124 On the other hand, to minimize the duration and magnitude of the exceedance above a 1.5°C level  
125 of warming (overshooting), the remaining carbon budget available for emissions is very small,  
126 implying that deeper global mitigation efforts are required immediately (next section; see also Table  
127 1 and Box 1).

128 The spatial dimension of 1.5°C warmer worlds is also important. Two worlds with similar global  
129 mean temperature anomalies may be associated with very different risks depending on how the

**Commented [TP1]:** Insert reference to Marzeion

Marzeion, B, G Kaser, F Maussion and N Champollion  
(accepted) Limited influence of climate change mitigation on  
short-term glacier mass loss  
Nature Climate Change

**Commented [TP2]:** Delete second associated?

130 associated regional temperature anomalies are distributed (Fig. 1b). Differential geographical  
131 responses in temperature are induced by: a) spatially varying radiative forcing (e.g. associated with  
132 land use<sup>19,20,21</sup> or aerosols<sup>22</sup>; b) differential regional feedbacks to the applied radiative forcing (e.g.  
133 associated with soil moisture-, snow, or ice feedbacks<sup>4,23</sup>); and/or c) regional climate noise<sup>24</sup> (e.g.  
134 associated with modes of variability or atmospheric weather variability). Similar considerations apply  
135 to regional changes in precipitation means and extremes, which are not globally homogeneous<sup>3,4</sup>.  
136 These regional temperature and precipitation anomalies and their rates of change determine the  
137 regional risks to human and natural systems and the challenges to adaptation which they face.

138 We note that mitigation, adaptation, and development pathways may result in spatially varying  
139 radiative forcing. While greenhouse gases are well mixed, changes in land use or air pollution may  
140 strongly affect regional climate. Land-use changes can be associated, for example, with the  
141 implementation of increased bioenergy plantations<sup>25</sup>, afforestation, reforestation, or deforestation,  
142 and their resulting impacts on local albedo or evapotranspiration; levels of aerosol concentrations  
143 may vary as a result of decreased air pollution<sup>22</sup>. Considering these regional forcings is essential  
144 when evaluating regional impacts, although there is still little available literature for 1.5°C warmer  
145 worlds, or low-emissions scenarios in general<sup>22,26,27,28</sup>. The spatial dimension of regional climates  
146 associated with a global warming of 1.5°C is also crucial when assessing risks associated with  
147 proposed climate engineering schemes based on solar radiation management (see hereafter). Beside  
148 the geographical distribution of changes in climate, non-temperature related changes are important,  
149 particularly where atmospheric CO<sub>2</sub> has additional and serious impacts through phenomena such as  
150 ocean acidification.

151

## 152 **Uncertainties of emissions pathways**

153 Emissions pathways that are currently considered to be compatible with limiting global warming to  
154 1.5°C<sup>12,13,14,15</sup> are selected based on their probability of limiting warming to below 1.5°C by 2100  
155 given current knowledge of how the climate system is likely to respond. Typically, this probability is  
156 set at 50% or 66% (i.e. 1/2 or 2/3 chances, respectively, of limiting warming in 2100 to 1.5°C or  
157 lower). The adequacy of these levels of probability is rather a political than a scientific question. This  
158 implies that even when diligently following such 1.5°C pathways from today onwards, there is  
159 considerable probability that the 1.5°C limit will be exceeded. This also includes some possibilities of  
160 warming being substantially higher than 1.5°C (see hereafter for the 10% worst-case scenarios).  
161 These risks of alternative climate outcomes are not negligible and need to be factored into the  
162 decision-making process.

163 Table 1 provides an overview of the outcomes of emissions pathways that are currently considered  
164 1.5°C- and 2°C-compatible with a specific probability<sup>15</sup> (and broadly consistent with the literature  
165 assessed in the IPCC AR5<sup>12,14</sup>, see Box 1 and Supplementary Information). Both “probable” (66<sup>th</sup>  
166 percentile, which remains below the respective temperature targets) and “worst-case” (10% worst,  
167 i.e. high-end) outcomes of these pathways are presented, including resulting global temperatures  
168 and regional climate changes (see next section and Box 1 for details, and Supplementary Information  
169 for median outcomes). The reported net cumulative CO<sub>2</sub> emissions characteristics for these scenario  
170 categories include effects of carbon dioxide removal options (CDR, also termed “negative  
171 emissions”<sup>29</sup>), which explains the decrease in cumulative CO<sub>2</sub> budgets after peak warming. Possible  
172 proposed CDR approaches include bioenergy use with carbon capture and storage (BECCS) or  
173 afforestation and changes in agricultural practice increasing carbon sequestration on land<sup>29</sup>. We note  
174 that the use of these approaches is controversial and could entail own sets of risks, for instance

related to competition for land use<sup>30,31</sup>. Their implementation is at present also still very limited, and the feasibility of their deployment as simulated in low-emissions scenarios has been questioned<sup>32</sup>. Current publications<sup>12,14,15</sup> indicate that scenarios in line with limiting year-2100 warming to below 1.5°C require strong and immediate mitigation measures and would require some degree and some kind of CDR. Alternative scenario configurations can be considered to limit the amount of CDR<sup>32</sup>. The current scenarios<sup>15</sup> as well as recent publications<sup>33,34,35</sup> provide updated cumulative CO<sub>2</sub> budgets estimates, which have larger remaining budgets compared to earlier estimates<sup>12,14</sup>. These, however, do not fundamentally change the need for strong near-term mitigation measures and technologies capable of enabling net-zero global CO<sub>2</sub> emissions near to mid-century if the considered emissions pathways are to be followed.

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## 186 Global and regional climate responses

Considering a subset of regions and extremes shown to retain particularly strong changes under a global warming of 1.5°C or 2°C<sup>4,36</sup>, Table 1 provides corresponding regional responses for the evaluated 1.5°C- and 2°C-compatible emissions pathways. The Figures 2 and 3 display associated regional changes for a subset of considered extremes: temperature extremes (coldest nights in the Arctic, warmest days in the contiguous United States) and in heavy precipitation (consecutive 5-day maximum precipitation in Southern Asia). Changes in hot extremes in Central Brazil and in drought occurrence in the Mediterranean region are additionally provided in Table 1. We note that the spread displayed for single scenario subsets in Figures 2 and 3 correspond to the spread of the global climate simulations of the 5<sup>th</sup> phase of the Coupled Model Intercomparison Project (CMIP5) underlying the derivation of the regional extremes for given global temperature levels<sup>4,36</sup> (see Box 1 for details).

In terms of the resulting global mean temperature increase, Figure 2 shows that the difference between the 10% “worst-case” and the “probable” (66%) outcome of the scenarios is substantial, both for the 1.5°C and 2°C scenarios. Interestingly, the “worst-case” outcomes from the 1.5°C scenarios are similar to the probable outcome of the 2°C scenarios. Indeed, both of these show less than 2°C warming by 2100, and approximately 2°C in the overshoot phase, while the warming in the overshoot phase can be slightly higher for the “worst-case” 1.5°C than for the probable 2°C scenarios assessed here. Hence, the scenarios aiming at limiting global warming to 1.5°C also have a clear relevance for limiting global warming to 2°C<sup>13</sup>, in that they ensure the 2°C threshold is not exceeded at the end of the 21<sup>st</sup> century. This contrasts with pathways designed to keep warming to 2°C, but have a 10% high-end (“worst-case”) warming of more than 2.4°C. This result is important when considering a 2°C warming as a “defence line” that should not be exceeded<sup>2</sup>.

Assessing changes in regional extremes illustrate the importance of considering the geographical distribution of climate change in addition to the global mean warming. Indeed, the average global warming does not convey the level of regional variability in climate responses<sup>4</sup>. By definition, because the global mean temperature is an average in time and space, there will be locations and time periods in which 1.5°C warming is exceeded even if the global mean temperature rise is restrained to 1.5°C. This is even already the case today, at about 1°C of global warming compared to the preindustrial period<sup>16</sup>. Similarly, some locations and time frames will display less warming than the global mean.

Extremes at regional scales can warm much more strongly than the global mean. For example, in scenarios compatible with 1.5°C global warming, minimum night-time temperatures (TNn) in the

Arctic increase by up to 5°C at peak warming if the “probable” (66<sup>th</sup> percentile) outcome of scenarios materializes, and up to 7°C if the “worst-case” (highest 10%, i.e. 90<sup>th</sup> percentile) outcome of the scenarios materializes (Fig. 2). For the “worst-case” outcome of scenarios considered 2°C compatible, the changes in these cold extremes is even larger, and can reach more than 8°C at peak warming (Fig. 2). While the change is more limited for hot extremes (annual maximum mid-day temperature, TXx) in the contiguous United States, it is also substantial there. At peak warming, these hot extremes increase by about 2.5°C for the probable 1.5°C scenarios (maximum in 66% of the cases), and exceeds 3°C warming for the “worst-case” 1.5°C scenarios and some of the “probable” 2°C scenarios. If the 10% “worst-case” temperature outcome materializes after following a pathway considered 2°C-compatible today, the temperature increase of the hottest days (TXx) can reach almost 4°C at peak global warming in that region (Fig. 2).

These analyses also reveal the level of inter-model range in regional responses, when comparing the full spread of the CMIP5 distributions (Fig. 2). This interquartile range reaches about 2°C for TNn in the Arctic and 1°C for TXx in the contiguous US at peak warming, i.e. it is 2-4 times larger than the difference in global warming at 1.5°C vs 2°C. The intermodel range is also very large for changes in heavy precipitation in Southern Asia (Fig. 2), with an approximate doubling of the response at peak warming for the 75<sup>th</sup> quantile in the most sensitive models compared to the 25<sup>th</sup> quantile in the least sensitive models. This highlights the fact that uncertainty in regional sensitivity to given global warming levels is an important component of uncertainty in impact projections (similarly as uncertainty in mitigation pathways or the global transient climate response). It also shows that even under most stringent mitigation pathways, some risk of dangerous changes in regional extremes (i.e. equivalent or stronger than responses at 2°C global warming) cannot be excluded.

Whilst most climate change risk assessments factor in the inter-model range of regional climate responses, relatively few consider the effects of extreme weather, for example the temperature increase of hottest days (TXx). Emerging literature highlights how these extreme events strongly influence levels of risk to human and natural systems, including crop yields<sup>37</sup> and biodiversity<sup>38</sup>, suggesting that the majority of risk assessments based on mean regional climate changes alone are conservative in that they do not incorporate the effects of extreme weather events. In addition, the co-occurrence of extreme events is also of high relevance for accurately assessing changes in risk, although analyses in this area are still lacking<sup>39,40</sup>.

Hence, the regional analyses of changes in extremes for scenarios aiming at limiting warming to 1.5°C and 2°C highlight the following main findings:

- Some regional responses of temperature extremes will be much larger than the changes in global mean temperature, with a factor of up to 3 (TNn in the Arctic).
- The regional responses at peak warming for scenarios that are considered today as compatible with limiting warming to 1.5°C (i.e. having 66% chance of stabilizing at 1.5°C by 2100) can still involve an extremely large increase in temperature in some locations and time frames, in the worst case up to 7°C for extreme cold night time temperatures or more than 3°C for daytime hot extremes (Fig. 2).
- The 10% highest response (“worst-case”) temperature outcome of pathways currently considered compatible with 1.5°C warming is comparable with the 66<sup>th</sup> percentile outcomes (“probable”) of scenarios that are considered for limiting warming below 2°C, at global and regional scales. This indicates that pursuing a 1.5°C compatible pathway can be considered a high-probability 2°C pathway<sup>13</sup> that strongly increases the probability of avoiding the risks of a 2°C warmer world.

## 265 Realization at single locations and times

266 The analyses of Figs. 2 and 3 represent the statistical response over longer time frames. Several  
267 dominant patterns of response are documented in the literature<sup>4</sup>, for instance that land  
268 temperatures tend to warm more than global mean temperature on average, in particular with  
269 respect to hot extremes in transitional regions between dry and wet climates, and coldest days in  
270 high-latitudes (see also Figs. 2 and 3). Nonetheless, due to internal climate variability (and in part  
271 model-based uncertainty), there may be large local departures from this typical response at single  
272 points in time (any given year within a 10-year time frame) as displayed in Fig. 4. Many locations  
273 show a fairly large probability (25% chance) of temperature anomalies below 1.5°C, and in some  
274 cases even smaller anomalies (mostly for the extreme indices). On the other hand, there is a similar  
275 probability (25%, for 75<sup>th</sup> percentile) that some locations can display temperature increases of more  
276 than 3°C, and in some cases up to 7-9°C for cold extremes. This illustrates that highly unusual and  
277 even unprecedented temperatures may occur even in a 1.5°C climate. While some of the patterns  
278 reflect what is expected from the median response<sup>4</sup>, the spread of responses is large in most  
279 regions.

280

## 281 Aspects insufficiently considered so far

282 The integrated assessment models used to derive the mitigation scenarios discussed here did not  
283 include several feedbacks that are present in the coupled Human-Earth system. This includes, for  
284 example, biogeophysical impacts of land use<sup>26,26,27</sup>, potential competition for land between negative  
285 emission technologies and agriculture<sup>29,31</sup>, water availability constraints on energy infrastructure and  
286 bioenergy cropping<sup>30,31</sup>, regional implications of choices of specific scenarios for tropospheric aerosol  
287 concentrations, or behavioural and societal changes in anticipation of or response to climate  
288 impacts<sup>41</sup>. For comprehensive assessments of the regional implications of mitigation and adaptation  
289 measures, such aspects of development pathways would need to be factored in.

290 We note also that non-CO<sub>2</sub> greenhouse gas emissions have to be reduced jointly with CO<sub>2</sub>. The  
291 numbers in Table 1 consider budgets for cumulative CO<sub>2</sub> emissions taking into account consistent  
292 evolutions for non-CO<sub>2</sub> greenhouse gas emissions. To compare the temperature outcome of  
293 pathways from many different forcings (e.g. methane, nitrous oxide), a CO<sub>2</sub>-only emission pathway  
294 that has the same radiative forcing can be found, which is termed CO<sub>2</sub>-forcing equivalent emissions  
295 (CO<sub>2</sub>-fe)<sup>42,43</sup>. Hence stronger modulation in non-CO<sub>2</sub> greenhouse gas emissions could be considered  
296 in upcoming scenarios.

297 Furthermore, a continuous adjustment of mitigation responses based on the observed climate  
298 response (that can e.g. reduce present uncertainties regarding the global transient climate response)  
299 might be necessary to avoid undesired outcomes. Pursuing such “adaptive” mitigation scenarios<sup>33</sup>  
300 would be facilitated by the Global Stocktake mechanism established in the Paris Agreement.  
301 Nonetheless, there are limits to possibilities for the adaptation of mitigation pathways, notably  
302 because some investments (e.g. in infrastructure) are long-term, and also because the actual  
303 departure from a desirable pathway will need to be detected against the backdrop of internal  
304 climate variability. The latter can be large on decadal time scales as highlighted with the recent so-  
305 called “hiatus” period<sup>44</sup>, but its impact can be minimized by using robust estimates of human-  
306 induced warming<sup>16</sup>. Hence, while adaptive mitigation pathways could provide some flexibility to  
307 avoid the highlighted “worst-case” scenarios (Table 1), it is not yet clear to which the extent they  
308 could be implemented in practice.



309 For a range of indicators, global mean temperature alone is not a sufficient indicator to describe  
310 climate impacts. CO<sub>2</sub> – sensitive systems, such as the terrestrial biosphere and agriculture systems,  
311 respond not only the impact of warming but also of increased CO<sub>2</sub> concentrations. Although the  
312 potential positive effects of CO<sub>2</sub> fertilisation are not well constrained<sup>45</sup>, it appears that the impacts of  
313 anthropogenic emissions on those systems will depend not only on the warming inferred, but also  
314 on the CO<sub>2</sub> concentrations at which these warming levels are reached. Similarly, impacts on marine  
315 ecosystems depend on warming as well as on changes being driven by ocean acidification<sup>46</sup>.

316 Impacts on ocean and cryosphere will respond to warming with a substantial time lag. As a  
317 consequence, ice sheet and glacier melting, ocean warming and as a result sea level rise will  
318 continue long after temperatures have peaked<sup>47</sup>. Large-scale oceanic systems will also continue to  
319 adjust over the coming centuries. One study identified as a result a continued increase of extreme El  
320 Niño frequency in a peak-and-decline scenario<sup>48</sup>. The imprints on such time-lagged systems for  
321 different 1.5°C worlds are not well constrained at present.

322

### 323 **Assessing solar radiation management (SRM)**

324 Compared to any mitigation options, climate interventions such as global solar radiation  
325 management (SRM) do not intend to reduce atmospheric CO<sub>2</sub> concentration per se but solely to limit  
326 global mean warming. Some studies<sup>49,50,51</sup> proposed that SRM may be used as a temporary measure  
327 to avoid global mean temperature exceeding 2°C. However, the use of SRM in the context of limiting  
328 temperature overshoot might create a new set of global and regional impacts, and could  
329 substantially modify regional precipitation patterns as compared to a world without SRM<sup>52,53</sup>. It  
330 would also have a high potential for cross-boundary conflicts because of positive, negative or  
331 undetectable effects on regional climate<sup>54</sup>, natural ecosystems<sup>55</sup> and human settlements. Hence,  
332 while the global mean temperature might be close to a 1.5°C warming, the regional implications  
333 could be very different from those of a 1.5°C global warming reached with early reductions of CO<sub>2</sub>  
334 emissions and stabilization of CO<sub>2</sub> concentrations. In some cases, some novel climate conditions  
335 would be created because of the addition of two climate forcings with different geographical  
336 footprints. Hence, a similar mean global warming may have very different regional implications (see  
337 Fig. 1b for an illustration) and in the case of SRM would be associated with substantial uncertainties  
338 in terms of regional impacts. Furthermore, SRM would not counter ocean acidification, which would  
339 continue unabated under enhanced CO<sub>2</sub> concentrations. Finally, there is also the issue that the  
340 sudden discontinuation of SRM measures would lead to a “termination problem”<sup>50,56</sup>. Together, this  
341 implies that the aggregated environmental implications of an SRM world with 1.5°C mean global  
342 temperature warming, would probably be very different, and likely more detrimental and less  
343 predictable, from those of a 1.5°C warmer world in which the global temperature is limited to 1.5°C  
344 through decarbonisation alone. Nonetheless, regional-scale changes in surface albedo may be  
345 worthwhile considering in order to reduce regional impacts in cities or agricultural areas<sup>21</sup>, although  
346 in-depth assessments on this topic are not yet available, and such modifications would be unlikely to  
347 substantially affect global temperature.

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### 350 **Risks in 1.5°C warmer worlds**

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352 1.5°C warmer worlds will still present risks to natural, managed, and human systems. The magnitude  
353 of these risks and their geographical patterns in a 1.5°C warmer world will not only depend on

uncertainties in the regional climate that result from this level of warming. The magnitude of risk will also strongly depend on the approaches used to limit warming to 1.5°C and on the wider context of societal development as it is pursued by individual communities and nations, and global society as a whole, which will result in significant differences in the magnitude and pattern of exposures and vulnerabilities<sup>57,58</sup>.

For natural ecosystems and agriculture, low-emissions scenarios can have a high reliance on land use modifications (either for bioenergy production or afforestation<sup>25,29,59</sup>) that in turn can affect food production and prices through land use competition effects<sup>29,31,60</sup>. The risks to human systems will depend on the ambition and effectiveness of implementing accompanying policies and measures that increase resilience to the risks of climate change and potential trade-offs of mitigation. For example, large scale deployment of BECCS could push the Earth closer to the planetary boundaries for land use change and freshwater, biosphere integrity and biogeochemical flows<sup>30</sup>.

Also the timing of when warming can be stabilized to 1.5°C or 2°C will influence exposure and vulnerability. For example, in a world pursuing a strong sustainable development trajectory, significant increases in resilience by the end of the century would make the world less vulnerable overall<sup>57</sup>. Even under this pathway, rapidly reaching 1.5°C would mean that some regions and sectors would require additional preparation to manage the hazards created by a changing climate.

#### **Commonalities of all 1.5°C warmer worlds**

Because human-caused warming linked to CO<sub>2</sub> emissions is near irreversible for more than 1000 years<sup>61,62</sup>, the cumulative amount of CO<sub>2</sub> emissions is the prime determinant to long-lived permanent changes in the global mean temperature rise at the Earth's surface. All 1.5°C stabilization scenarios require net CO<sub>2</sub> emissions to be zero and non-CO<sub>2</sub> forcing to be capped to stable levels at some point<sup>61,63,64</sup>. This is also the case for stabilization scenarios at higher levels of warming (e.g. at 2°C), the only differences would be the time at which the net CO<sub>2</sub> budget is zero, and the cumulative CO<sub>2</sub> emissions emitted until then. Hence, a transition to a decarbonisation of energy use is necessary in all scenarios.

Article 4 of the Paris Agreement calls for net zero global greenhouse gas emissions to be achieved in the second half of the 21<sup>st</sup> century, which most plausibly requires some extent of negative CO<sub>2</sub> emissions to compensate for remaining non-CO<sub>2</sub> forcing<sup>13</sup>. The timing of when net zero global greenhouse gas emissions are achieved strongly determines the peak warming. All published 1.5°C-warming compatible scenarios include CDR to achieve net-zero CO<sub>2</sub> emissions, to varying degrees. CO<sub>2</sub>-induced warming by 2100 is determined by the difference between the total amount of CO<sub>2</sub> generated (which can be reduced by early decarbonisation) and the total amount permanently stored out of the atmosphere, for example by geological sequestration. Current evidence indicates that at least some measure of CDR will be required to follow a 1.5°C-compatible emissions trajectory.

#### **Towards a sustainable "1.5°C warmer world"**

Emissions pathways limiting global warming to 1.5°C allow to avoid risks associated with higher levels of warming, but do not guarantee an absence of climate risks at regional scale, and are also associated with their own set of risks with respect to the implementation of mitigation technologies, in particular related to land use changes associated with e.g. BECCS or competition for food production<sup>29,30,31</sup>.

400 Important aspects to consider when pursuing limiting warming to or below a global mean  
401 temperature level relate to how this goal is achieved and to the nature of emerging regional and  
402 sub-regional risks<sup>65,66,67</sup>. Also relevant are considerations of how the policies influence the resilience  
403 of human and natural systems, and which broader societal pathways are followed in terms of human  
404 development. Many but not all of these can be influenced directly through policy choices<sup>65,66,67</sup>.  
405 Internal climate variability as well as regional climate sensitivity, which display a substantial range  
406 between current climate models, are also important components of how risk will be realized.  
407 Explicitly illustrating the full range of possible outcomes of 1.5°C warmer worlds is important for an  
408 adequate consideration of the implications of mitigation options by decision makers.

409 The time frame to initiate major mitigation measures varies in 1.5°C-compatible (or 2°C) scenarios  
410 (Table 1). However, given the current state of knowledge about both the global and regional climate  
411 responses and the availability of mitigation measures, if the potential to limit warming to below  
412 1.5°C or 2°C is to be maximised, emissions reductions in CO<sub>2</sub> and other greenhouse gases would  
413 need to start as soon as possible, leading to a global decline in emissions following 2020 at the  
414 latest. At the same time, if potential competition for land and water between negative emission  
415 technologies, agriculture and biodiversity conservation is to be avoided, mitigation would need to be  
416 carefully designed and regulated to minimise these effects, which could otherwise act to increase  
417 food prices and reduce ecosystem services. The remaining uncertainties underscore the need for  
418 continuous monitoring of not just global mean surface temperature, but also of the deployment and  
419 development of mitigation options, the resulting emissions reductions, and in particular of the  
420 intensity of global and regional climate responses and their sensitivity to climate forcing. As shown  
421 here, together with the overall societal development choices, these various elements strongly co-  
422 determine the regional and sectoral magnitudes and patterns of risk at 2°C and 1.5°C global  
423 warming.

424   **References**

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426   Contribution of Working Group I to2 the Fifth Assessment Report of the Intergovernmental Panel on  
427   Climate Change (eds Stocker, T. F. et al.) 3–29 (Cambridge Univ. Press, 2013).  
428   [UPDATE REFERENCES]  
429

430 **Acknowledgements**

431 S.I.S. and R.W. acknowledge the European Research Council (ERC) 'DROUGHT-HEAT' project funded by the  
432 European Community's Seventh Framework Programme (grant agreement FP7-IDEAS-ERC-617518). J.R.  
433 acknowledges the Oxford Martin School Visiting Fellowship programme for support. R.S. acknowledges the  
434 European Union's H2020 project CRESCENDO "Coordinated Research in Earth Systems and Climate:  
435 Experiments, kNowledge, Dissemination and Outreach" (grant agreement H2020-641816). O.H.G.  
436 acknowledges support of the Australia Research Council Laureate program. This work contributes to the World  
437 Climate Research Programme (WCRP) Grand Challenge on Extremes. We acknowledge the WCRP Working  
438 Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for  
439 producing and making available their model output. For CMIP the US Department of Energy's Program for  
440 Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software  
441 infrastructure in partnership with the Global Organization for Earth System Science Portals.  
442  
443  
444

445 **Data availability**

446 Emission data is available from the database accompanying ref<sup>15</sup> which presents pathways in line with 1.9  
447 W/m<sup>2</sup> of radiative forcing in 2100, limiting warming to below 1.5°C by 2100. Regional changes in climate  
448 extremes for different global warming levels derived following the methodology of refs<sup>4,36</sup> can be obtained  
449 from the associated database associated with the ERC DROUGHT-HEAT project ([http://www.drought-](http://www.drought-heat.ethz.ch)  
450 [heat.ethz.ch](http://www.drought-heat.ethz.ch)) and the software developed under ref<sup>36</sup>.  
451  
452  
453

454 **Authors contributions**

455  
456 S.I.S. coordinated the design and writing of the article, with inputs from all co-authors. J.R. provided the  
457 emissions scenario data processed in Table 1. R.S. computed the scenario summary statistics of Table 1. R.W.  
458 computed the regional projections statistics of Table 1, as well as Figs. 2-4. J.R., R.S., M.A, M.C and R.M.  
459 provided essential insights on emissions scenarios. S.I.S. prepared Fig. 1, with support from P.T. and J.R. S.I.S.  
460 drafted the first version of the manuscript, with inputs from J.R., R.S. and M.A. All authors contributed to and  
461 commented on the manuscript.

462 **Box 1. Emissions budgets and regional projections for 1.5°C and 2°C global warming**

463 The emissions budget estimates provided in Table 1 are based on scenarios currently considered compatible  
464 with limiting global warming to 1.5°C and 2°C, either in 2100 or during the entire 21<sup>st</sup> century<sup>15</sup>. For these  
465 estimates, emissions pathways compatible with a 1.5°C or 2°C global warming are determined based on their  
466 probability of limiting the global temperature anomaly below 1.5°C or 2°C by 2100 using the probabilistic  
467 outcomes of a simple climate model (MAGICC<sup>68</sup>) exploring the range of climate system response as assessed in  
468 the Working Group I contribution to the IPCC 5<sup>th</sup> assessment report (IPCC AR5)<sup>69</sup>.

470 The global transient climate response (TCR) values corresponding to the 50<sup>th</sup> (see Supplementary Information),  
471 66<sup>th</sup> and 90<sup>th</sup> percentile (Table 1) responses in the scenarios are 1.7 [°C/ 1000 GtC], 1.9 [°C/1000 GtC], and 2.4  
472 [°C/1000 GtC], overall consistent with the assessed range for this parameter (1-2.5 [°C/1000 GtC]) in the IPCC  
473 AR5<sup>69</sup>. The current airborne fraction (ratio of accumulated atmospheric CO<sub>2</sub> to CO<sub>2</sub> emissions over the decade  
474 2011-2020) in these scenarios with this version of the MAGICC model is 0.55, which is 20% higher than the  
475 central estimate given in refs<sup>70,71</sup>, but ref<sup>71</sup> emphasises that this quantity is uncertain and subject to variability  
476 over time.

478 The provided estimates are consistent with corresponding values derived from scenarios assessed in the  
479 Working Group III contribution to the IPCC AR5<sup>12,14</sup> (see Suppl. Information), but have slightly larger estimates  
480 for the remaining cumulative CO<sub>2</sub> budgets, consistent with other recent publications<sup>33,34,35</sup>. Both sets of  
481 scenarios imply that for limiting global temperature warming below 1.5°C by the end of the century strong  
482 near-term mitigation measures are needed supported by technologies capable of enabling net-zero global CO<sub>2</sub>  
483 emissions near to mid-century.

485 Table 1 also provides estimates of regional responses associated with given levels of global temperature  
486 warming (at peak warming and in 2100). The values are computed based on decadal averages of global climate  
487 model simulations from the CMIP5 experiment following the approach from refs<sup>4,36</sup>. Decades corresponding to  
488 a 1.5°C or 2°C warming are those in which the last year of the decade reaches this temperature, consistent  
489 with previous publications<sup>3,4,36</sup>. The considered climate extremes indicators include warming of the minimum  
490 annual night-time temperature (TNn) in the Arctic land [°C], the warming of the maximum annual day-time  
491 temperature (TXx) in the contiguous United States [°C], TXx warming in Central Brazil [°C], (soil moisture)  
492 drying in the Mediterranean region [in units of standard deviations of late 20<sup>th</sup> century variability], and  
493 increases in heavy precipitation events based on annual maximum consecutive 5-day precipitation (Rx5day) in  
494 Southern Asia [%]]. See ref<sup>4</sup> for a definition of the geographical domains. The estimates are derived from ....  
495 CMIP5 models (see ref<sup>36</sup>).

497 The databases underlying the analyses of Table 1 and Figs. 2-3 are described under the data availability  
498 statement. The R code used to analyze MAGICC outputs in this paper is available from R.S. on reasonable  
499 request. The scripts used for the regional analyses provided in Table 1 and Figs 2-4 are available from S.I.S. and  
500 R.W. upon request.

501

502

**Commented [SIS3]:** Myles, Joeri, Roland: OK? Are the units correct (°C/1000 GtC)? (NB: The AR5 notes a range of 0.8-2.5 °C/1000 GtC for TCRe in the SPM but 1-2.5 for TCR in the technical summary – Are TCR and TCRe different?)

**Commented [SIS4]:** Richard W., please specify the number of underlying CMIP5 models and scenarios (only RCP8.5, or all scenarios?)

503 **List of Tables**

504

505 **Table 1: Description of different worlds based on scenarios currently considered compatible with 1.5°C and**  
506 **2°C warming<sup>15</sup>, including projections of changes in regional climate associated with resulting global**  
507 **temperature levels derived following previous studies<sup>4,36</sup> (see Supplementary Information for corresponding**  
508 **estimates from scenarios assessed in the IPCC 5<sup>th</sup> assessment report<sup>12,14</sup> and for median estimates).**

509

510

Table 1: Description of different worlds based on scenarios currently considered compatible with 1.5°C and 2°C warming<sup>15</sup>, including projections of changes in regional climate associated with resulting global temperature levels derived following previous studies<sup>4,36</sup> (see Supplementary Information for corresponding estimates from scenarios assessed in the IPCC 5<sup>th</sup> assessment report<sup>12,14</sup> and for median estimates).

		SCEN_1p5C Emissions pathways currently considered in line with keeping warming below 1.5°C in 2100 with 66% chance (allowing for a higher peak in temperature earlier)		SCEN_2C Emissions pathways currently considered in line with keeping warming below 2°C during the entire 21 <sup>st</sup> century with 66% chance	
		"probable" (66 <sup>th</sup> percentile) outcome <sup>a</sup>	"worst-case" 10% (90 <sup>th</sup> percentile) outcome <sup>b</sup>	"probable" (66 <sup>th</sup> percentile) outcome <sup>a</sup>	"worst-case" 10% (90 <sup>th</sup> percentile) outcome <sup>b</sup>
General characteristics of pathway	Overshoot 1.5°C in 21 <sup>st</sup> century with >50% likelihood <sup>c,h</sup>	Yes (13/13)	Yes (13/13)	Yes (10/10)	Yes (10/10)
	Overshoot 2°C in 21 <sup>st</sup> century with >50% likelihood <sup>h</sup>	No (0/13)	Yes (10/13)	No (0/10)	Yes (10/10)
	Cumulative CO <sub>2</sub> emissions up to peak warming (relative to 2016) <sup>d</sup>	720 (650, 750)	690 (650, 710)	1050 (1020, 1140)	1040 (930, 1140)
	Cumulative CO <sub>2</sub> emissions up to 2100 (relative to 2016) <sup>e</sup> [GtCO <sub>2</sub> ]	320 (200, 340)		1030 (910, 1140)	
	Global GHG emissions in 2030 <sup>d</sup> [GtCO <sub>2</sub> y <sup>-1</sup> ]	22 (19, 31)		28 (24, 30)	
	Years of global net zero CO <sub>2</sub> emissions <sup>d</sup>	2070 (2067, 2074)		2088 (2085, 2092)	
Possible climate range at peak warming (reg+glob)	Global mean temperature anomaly at peak warming [°C]	1.75°C (1.65, 1.81°C)	2.13°C (2.0, 2.2°C)	1.93°C (1.9, 1.94°C)	2.44°C (2.43, 2.46°C)
	Warming in the Arctic <sup>e</sup> (TNn <sup>f</sup> ) [°C]	5.04°C (4.45, 5.66°C)	6.29°C (5.47, 7.21°C)	5.70°C (4.90, 6.53°C)	7.25°C (6.51, 8.24°C)
	Warming in the contiguous United States <sup>e</sup> (TXx <sup>f</sup> ) [°C]	2.57°C (2.04, 2.95°C)	3.09°C (2.71, 3.58°C)	2.83°C (2.34, 3.27°C)	3.63°C (3.23, 3.98°C)
	Warming in Central Brazil <sup>e</sup> (TXx <sup>f</sup> ) [°C]	2.74°C (2.39, 3.22°C)	3.34°C (3.05, 3.92°C)	3.01°C (2.62, 3.50°C)	3.82°C (3.44, 4.15°C)
	Drying in the Mediterranean region <sup>e</sup> [std <sup>f</sup> ] (-1: dry; -2: severely dry; -3: very severely dry)	-1.27 (-2.43, -0.45)	-1.40 (-2.64, -0.52)	-1.14 (-2.18, -0.50)	-1.42 (-2.74, -0.67)
	Increase in heavy precipitation events <sup>f</sup> in Southern Asia <sup>e</sup> [%]	9.69% (6.79, 14.90%)	12.87% (7.90, 22.78%)	10.01% (6.97, 17.11%)	17.45% (10.15, 24.03%)
Possible climate range in 2100 (reg+glob)	Global mean temperature warming in 2100 [°C] <sup>l</sup>	1.44°C (1.44—1.48°C)	1.88°C (1.85—1.93°C)	1.89°C (1.88—1.91°C)	2.43°C (2.42—2.46°C)
	Warming in the Arctic <sup>e</sup> (TNn <sup>f</sup> ) [°C]	4.21°C (3.65, 4.71°C)	5.55°C (4.80, 6.35°C)	5.58°C (4.82, 6.38°C)	7.22°C (6.49, 8.16°C)
	Warming in the contiguous United States <sup>e</sup> (TXx <sup>f</sup> ) [°C]	2.03°C (1.64, 2.49°C)	2.73°C (2.21, 3.22°C)	2.76°C (2.23, 3.24°C)	3.64°C (3.23, 3.97°C)
	Warming in Central Brazil <sup>e</sup> (TXx <sup>f</sup> ) [°C]	2.25°C (2.02, 2.60°C)	2.92°C (2.55, 3.44°C)	2.94°C (2.58, 3.47°C)	3.80°C (3.43, 4.12°C)
	Drying in the Mediterranean region <sup>e</sup> [std <sup>f</sup> ]	-0.96 (-1.94, -0.28)	-1.09 (-2.16, -0.48)	-1.10 (-2.15, -0.46)	-1.41 (-2.69, -0.64)
	Increase in heavy precipitation events <sup>f</sup> in Southern Asia <sup>e</sup> [%]	8.29% (4.52, 11.98%)	10.59% (6.75, 16.64%)	10.55% (6.83, 16.64%)	17.21% (10.24, 24.03%)

<sup>a</sup> 66<sup>th</sup> percentile for global temperature (i.e. 66% likelihood of being at or below threshold)

<sup>b</sup> 90<sup>th</sup> percentile for global temperature (i.e. 10% likelihood of being at or above threshold)

<sup>c</sup> All 1.5°C scenarios include a substantial probability of overshooting above 1.5°C global warming before returning to 1.5°C.

<sup>d</sup> The values indicate the median and the interquartile range in parenthesis (25<sup>th</sup> percentile and 75<sup>th</sup> percentile)

<sup>e</sup> The regional projections in these rows provide the range [median (q25, q75)] associated with the *median* global temperature outcomes of the considered mitigation scenarios at *peak warming* (see Box 1 for details).

<sup>f</sup> TNn: annual minimum night-time temperature; TXx: annual maximum day-time temperature; std: drying of soil moisture expressed in units of standard deviations of late 20<sup>th</sup> century variability; Rx5day: annual maximum consecutive 5-day precipitation (see Box 1 for details)

<sup>g</sup> Same as footnote e, but for the regional responses associated with the *median* global temperature outcomes of the considered mitigation scenarios *in 2100* (see Box 1 for details).

<sup>h</sup> Red and yellow colors indicate whether scenarios lead to overshoot a given level of warming or not.

<sup>l</sup> Green, yellow and red colors indicate whether the global mean temperature remains below 1.5°C, between 1.5°C and 2°C, or exceeds 2°C.

Commented [SIS5]: Richard: Which time frame?



530 **List of Figures**

531  
532 **Figure 1. Temporal and spatial dimensions 1.5°C warmer worlds.** **a.** Typical pathways of Earth’s climate  
533 towards stabilization at 1.5°C warming. Pre-industrial climate conditions are the reference for the determined  
534 global warming. Present-day warming corresponds to 1°C compared to pre-industrial conditions. All “1.5°C-  
535 warming compatible emissions pathways” currently available in the literature<sup>12,13,14,15</sup> include overshooting  
536 over 1.5°C warming prior to stabilization or further decline. We here illustrate the example of temperature  
537 stabilization at 1.5°C in the long-term, but temperatures could also further decline below 1.5°C. **b.** Not all  
538 conceivable “1.5°C warmer climates” are equivalent. These conceptual schematics illustrate the importance of  
539 the spatial dimension of distributed impacts associated with a given global warming, at the example of a  
540 simplified world with two surfaces of equal area (the given temperature anomalies are chosen for illustrative  
541 purposes and do not refer to specific 1.5°C scenarios). (left) Reference world (without warming); (top right)  
542 world with 1.5°C mean global warming that is equally distributed on the two surfaces; (bottom right) world  
543 with 1.5°C mean global warming with high differences in regional responses.

544

545 **Figure 2: Possible outcomes with respect to global temperature and regional climate anomalies from typical**  
546 **1.5°C-warming and 2°C-warming compatible scenarios at peak warming.** Top: Net GtCO<sub>2</sub> emitted until time of  
547 peak warming relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios  
548 from Table 1 (25<sup>th</sup> quantile (q25), median (q50), and 75<sup>th</sup> quantile (q75)). 2<sup>nd</sup> row: Global mean temperature  
549 anomaly at peak warming (q25, q50, q75). 3<sup>rd</sup>-5<sup>th</sup> row: Regional climate anomalies at peak warming compared  
550 to the pre-industrial period corresponding to the median global warming of the 2<sup>nd</sup> row (full range associated  
551 with different regional responses within CMIP5 multi-model ensemble displayed as violin plot; the median and  
552 interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.

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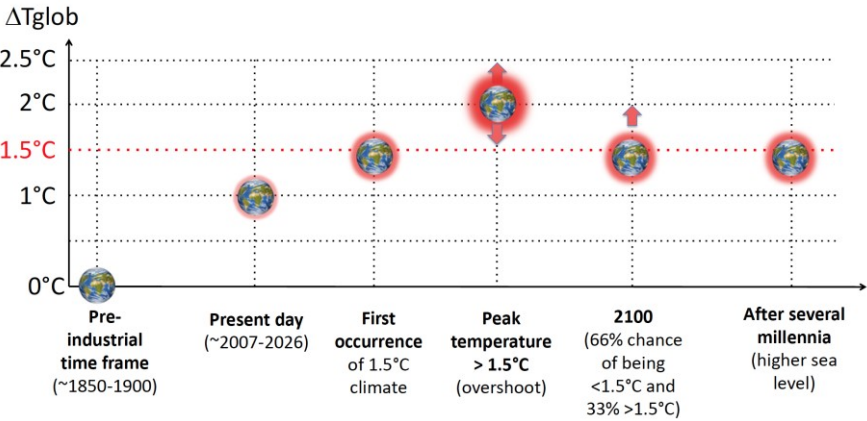
554 **Figure 3: Possible outcomes with respect to global temperature and regional climate anomalies from typical**  
555 **1.5°C-warming and 2°C-warming compatible scenarios in 2100.** Top: Net GtCO<sub>2</sub> emitted by 2100 relative to  
556 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1  
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561 indicated with horizontal dark gray lines). See Table 1 for more details.

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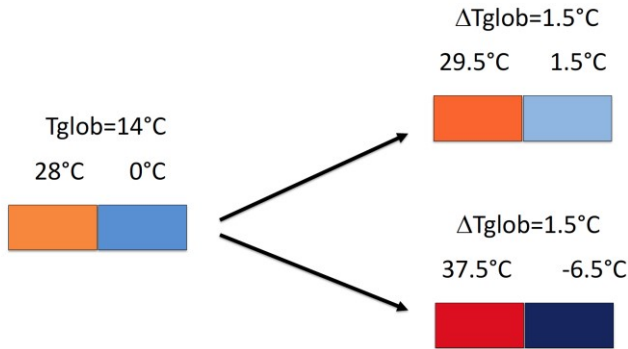
563 **Figure 4: The stochastic noise and model-based uncertainty of realized climate at 1.5°C.** Temperature with  
564 25% chance of occurrence at any location within 10-year time frames corresponding to  $\Delta T_{glob}=1.5^{\circ}C$  (based on  
565 CMIP5 multi-model ensemble). The plots display at each location the 25<sup>th</sup> percentile (Q25, left) and 75<sup>th</sup>  
566 percentile (Q75, right) values of mean temperature (Tmean), yearly maximum day-time temperature (TXx),  
567 yearly minimum night-time temperature (TNn), sampled from all time frames with  $\Delta T_{glob}=1.5^{\circ}C$  in RCP8.5  
568 model simulations of the CMIP5 ensemble.

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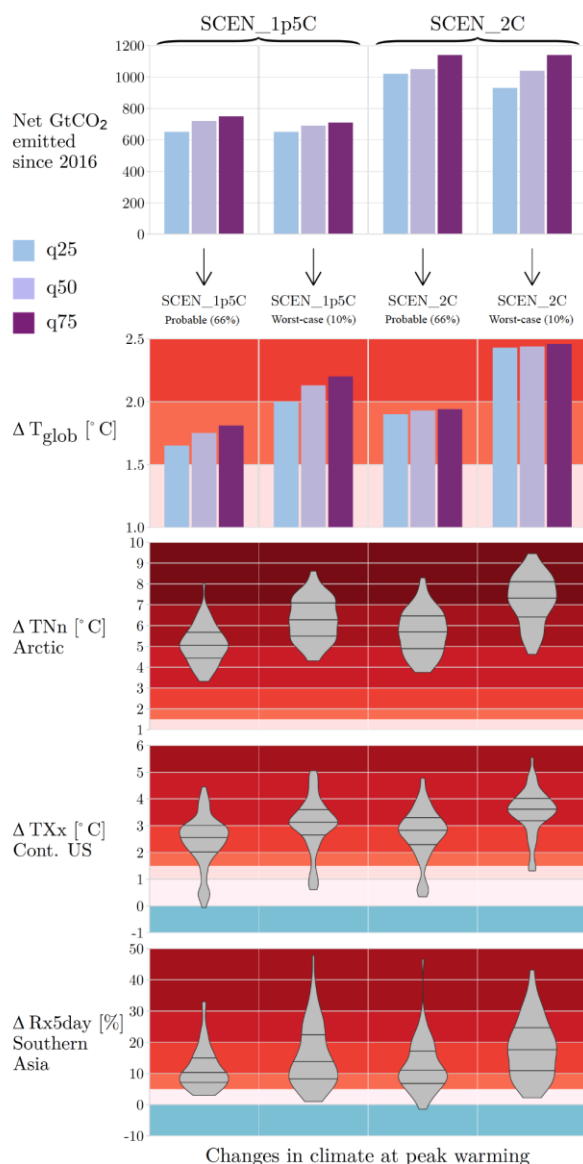
**a Temporal dimension of "1.5°C warmer worlds"**



**b Spatial dimension of "1.5°C warmer worlds" (hypothetical example)**



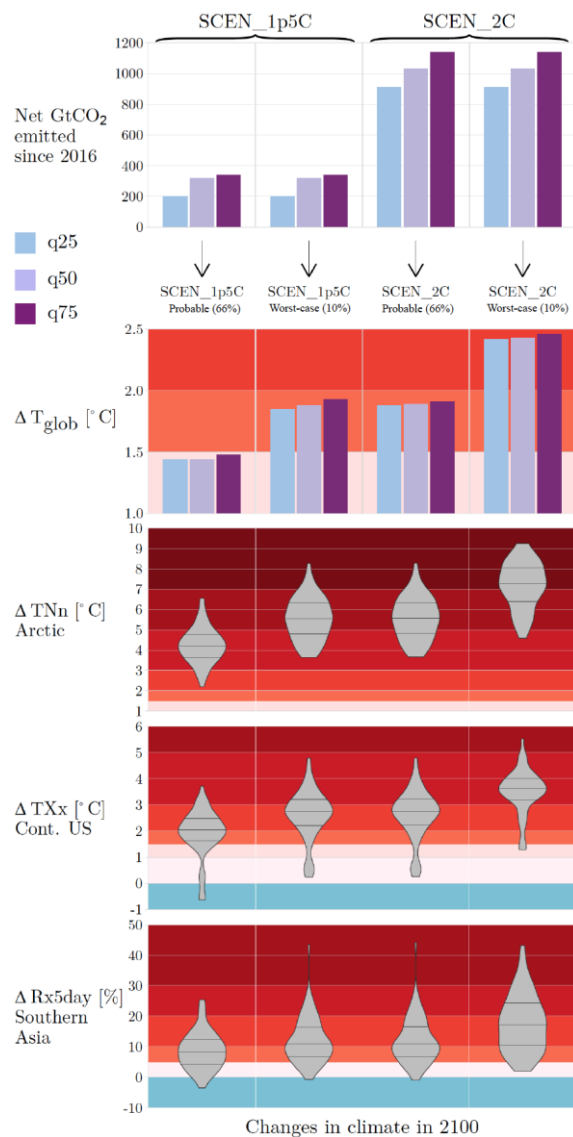
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584

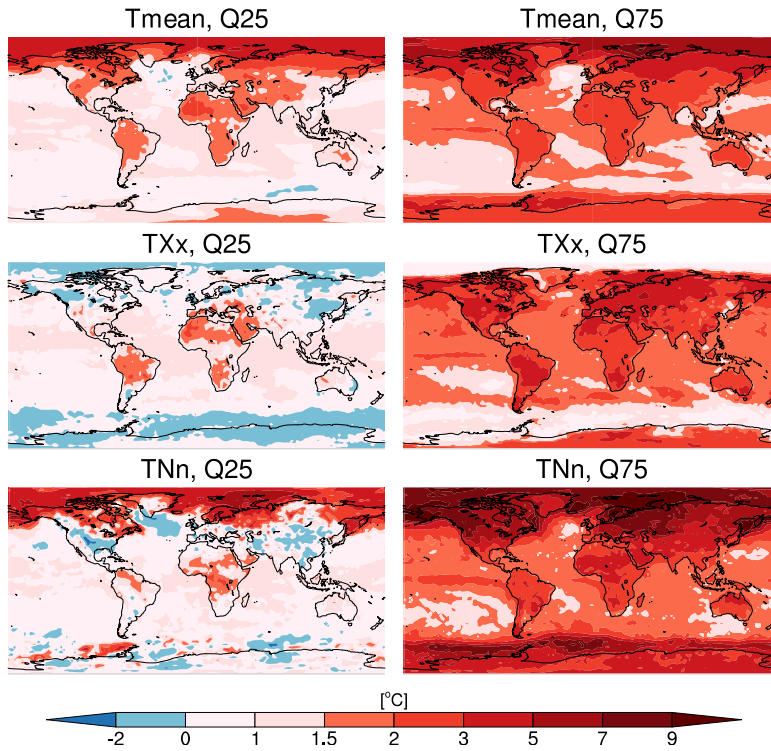
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 592 interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.

**Commented [SIS6]:** Richard: Can you please add letter labels ("a", "b", ...) to the different panels (see editor's comments)



**Figure 3: Possible outcomes with respect to global temperature and regional climate anomalies from typical 1.5°C-warming and 2°C-warming compatible scenarios in 2100.** Top: Net GtCO<sub>2</sub> emitted by 2100 relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1 (25<sup>th</sup> quantile (q25), median (q50), and 75<sup>th</sup> quantile (q75)). 2<sup>nd</sup> row: Global mean temperature anomaly in 2100 (q25, q50, q75). 3<sup>rd</sup>-5<sup>th</sup> row: Regional climate anomalies at peak warming compared to the pre-industrial period corresponding to the median global warming of the 2<sup>nd</sup> row (full range associated with different regional responses within CMIP5 multi-model ensemble displayed as violin plot; the median and interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.

Temperatures with 25% chance of occurring in any 10-year period with  $\Delta T = 1.5^\circ\text{C}$  (CMIP5 ensemble)



**Figure 4: The stochastic noise and model-based uncertainty of realized climate at 1.5°C.** Temperature with 25% chance of occurrence at any location within 10-year time frames corresponding to  $\Delta T_{\text{glob}}=1.5^\circ\text{C}$  (based on CMIP5 multi-model ensemble). The plots display at each location the 25<sup>th</sup> percentile (Q25, left) and 75<sup>th</sup> percentile (Q75, right) values of mean temperature (Tmean), yearly maximum day-time temperature (TXx), yearly minimum night-time temperature (TNn), sampled from all time frames with  $\Delta T_{\text{glob}}=1.5^\circ\text{C}$  in all RCP8.5 model simulations of the CMIP5 ensemble.

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